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**Lee et al.**

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(45) **Date of Patent: Jan. 12, 2016**

(54) **OPTICAL IMPAIRMENT AWARE PATH COMPUTATION ARCHITECTURE IN PCE BASED NETWORK**

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(22) Filed: **Jan. 13, 2012**

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***H04L 12/28*** (2006.01)
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CPC ......... ***H04J 14/0246*** (2013.01); ***H04J 14/0257*** (2013.01); ***H04J 14/0267*** (2013.01); ***H04J 14/0271*** (2013.01); ***H04L 45/00*** (2013.01); ***H04L 45/22*** (2013.01); ***H04L 45/28*** (2013.01); ***H04L 45/42*** (2013.01); ***H04L 45/50*** (2013.01); ***H04L 45/62*** (2013.01); ***H04Q 11/0062*** (2013.01); *H04J 14/0221* (2013.01);
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(58) **Field of Classification Search**
None
See application file for complete search history.

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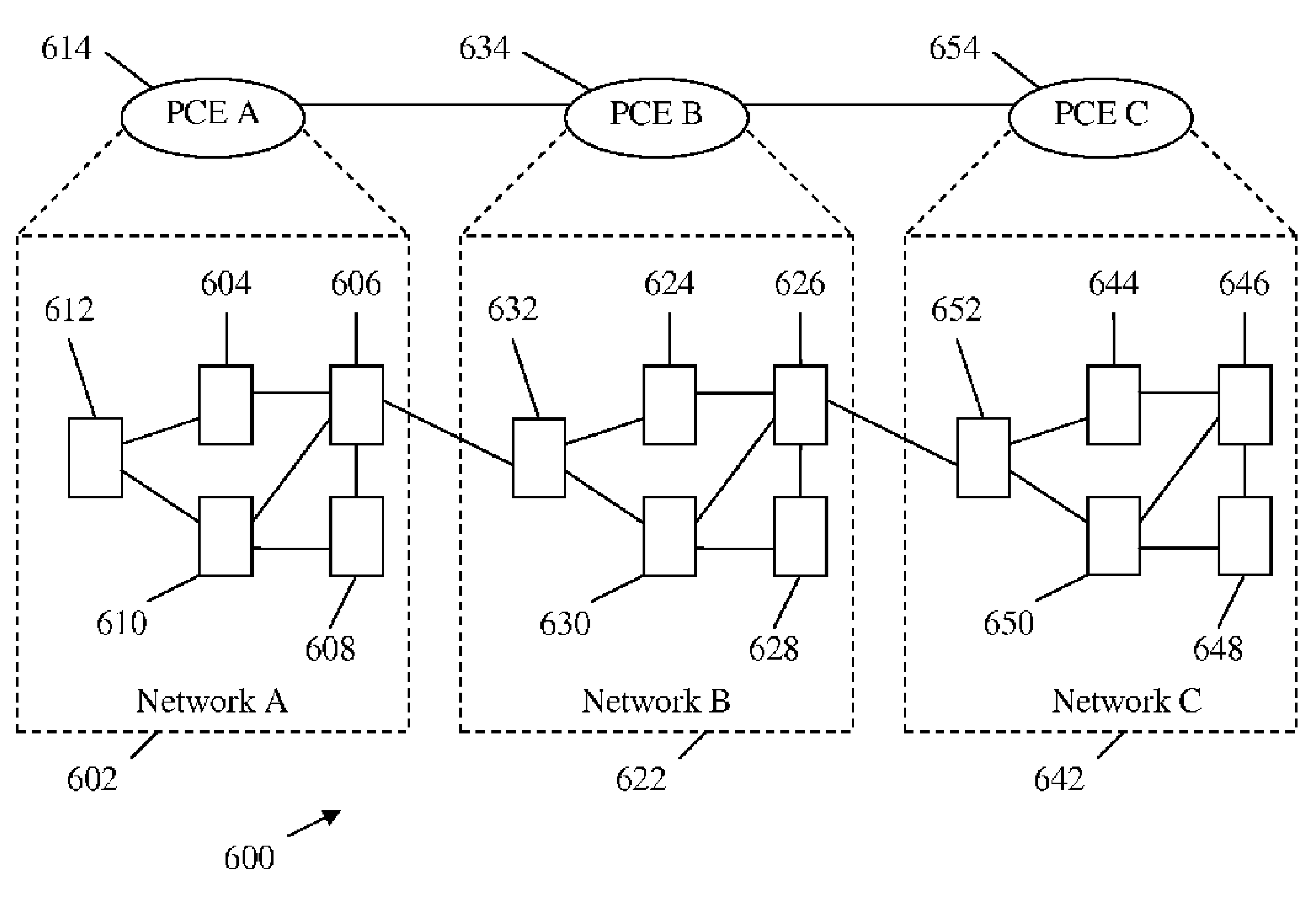
(57) **ABSTRACT**

An apparatus comprising at least one processor configured to implement a method comprising receiving a path computation request comprising at least one path computation constraint, and determining whether there is a path through an optical network that satisfies the path computation constraints. Also disclosed is an apparatus configured to process a data structure comprising a flags field comprising at least one flag having one of an active state or an inactive state, wherein each flag is representative of an optical quality constraint.

**16 Claims, 8 Drawing Sheets**



(51) **Int. Cl.**
***H04J 14/02*** (2006.01)
***H04L 12/701*** (2013.01)
***H04L 12/707*** (2013.01)
***H04L 12/703*** (2013.01)
***H04L 12/717*** (2013.01)
***H04L 12/723*** (2013.01)
***H04L 12/721*** (2013.01)
***H04Q 11/00*** (2006.01)

(52) **U.S. Cl.**
CPC .......... *H04J14/0258* (2013.01); *H04J 14/0269* (2013.01); *H04J 14/0284* (2013.01); *H04Q 2011/0064* (2013.01); *H04Q 2011/0073* (2013.01); *H04Q 2011/0088* (2013.01)

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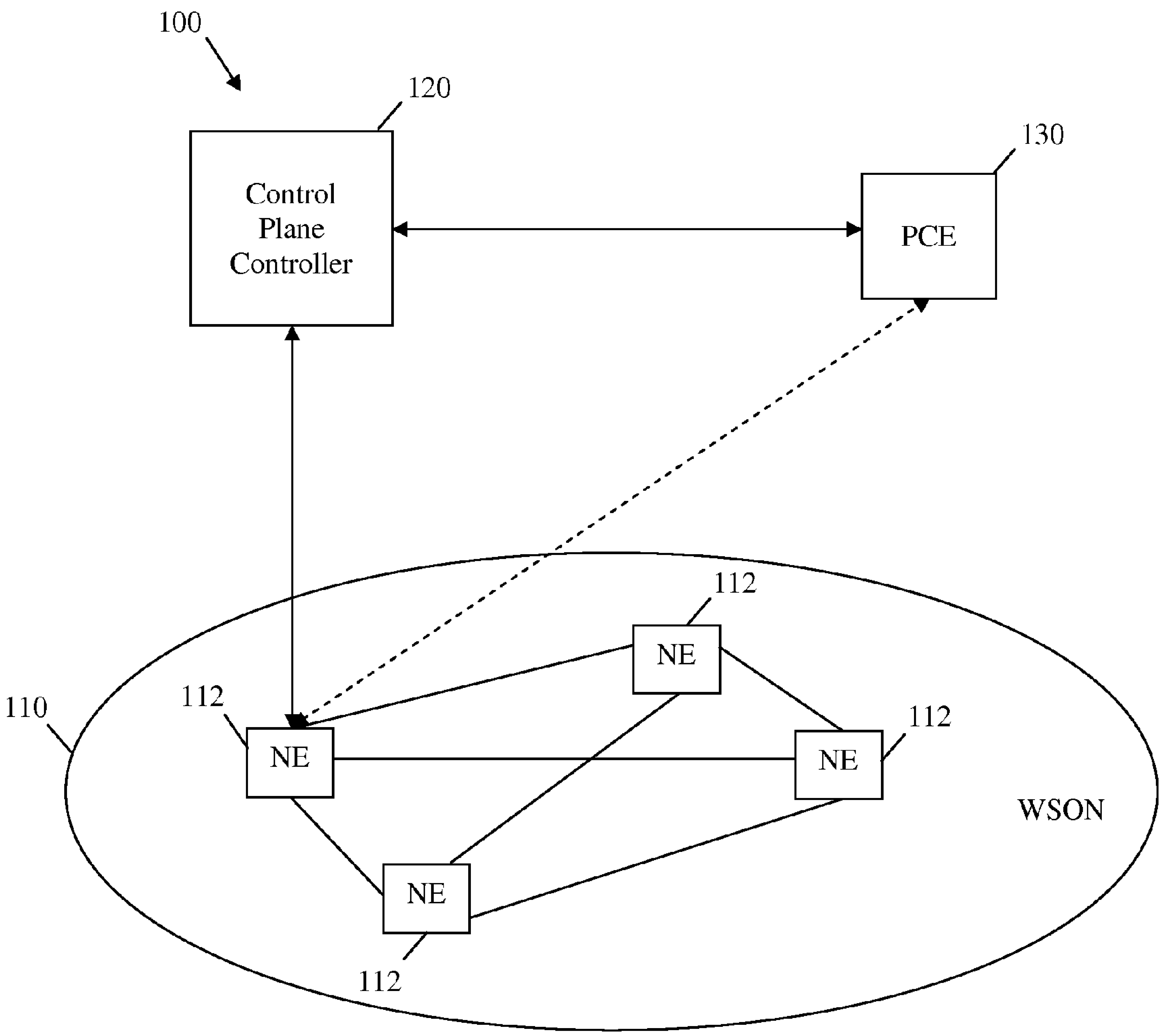

100
120
Control
Plane
Controller
130
PCE
112
NE
110
112
NE
112
NE
WSON
NE
112

FIG. 1

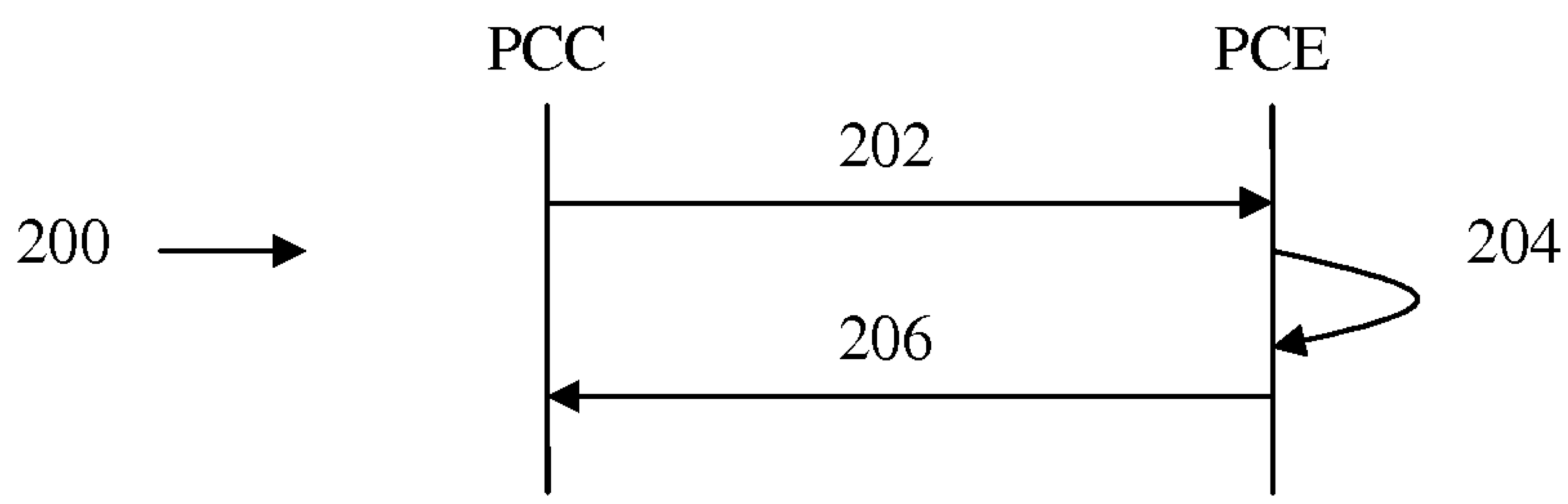



FIG. 2

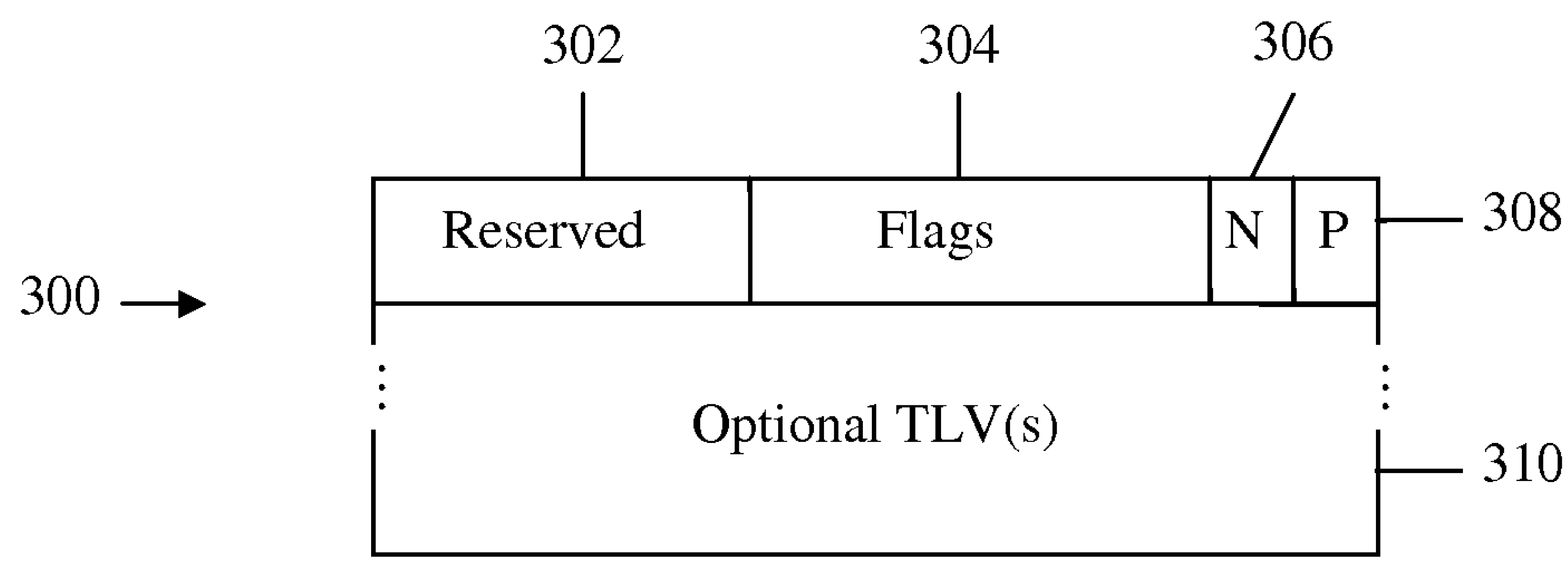



FIG. 3

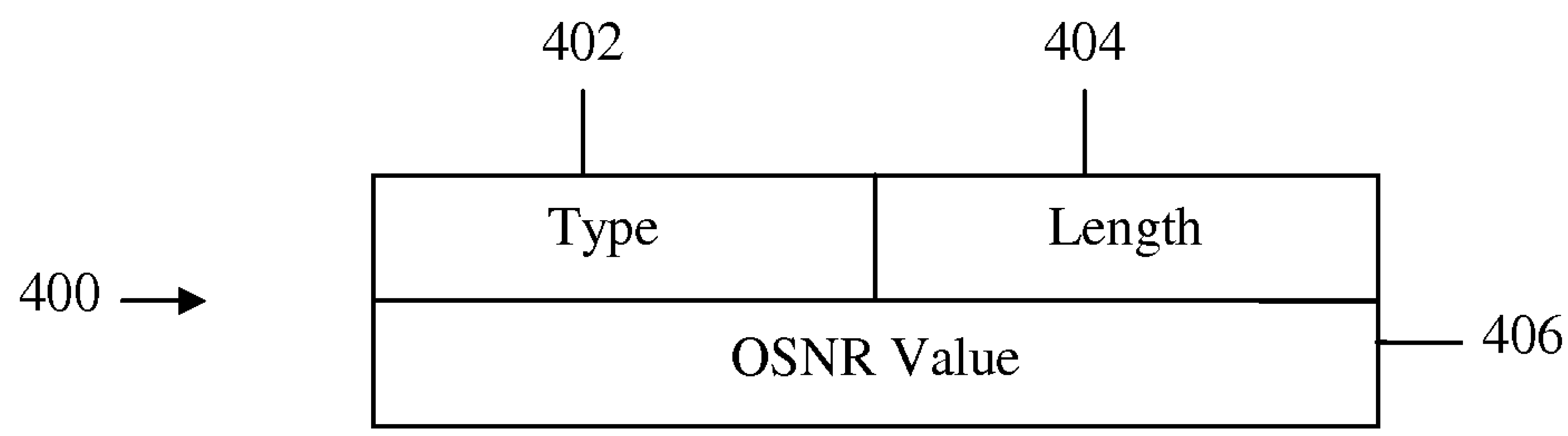
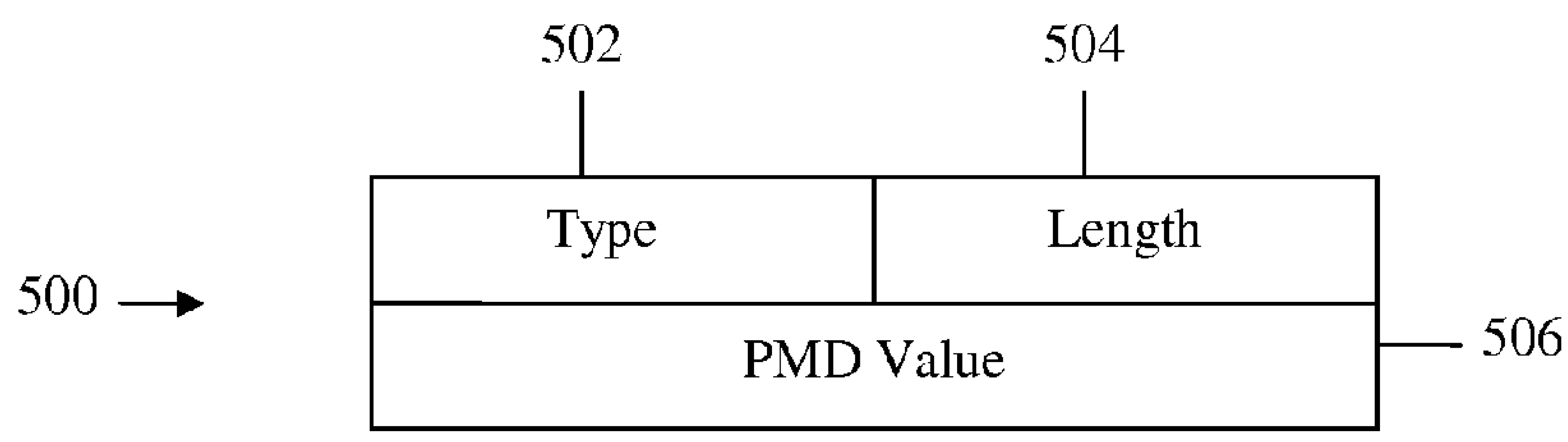



FIG. 4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504
Type
Length
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PMD Value
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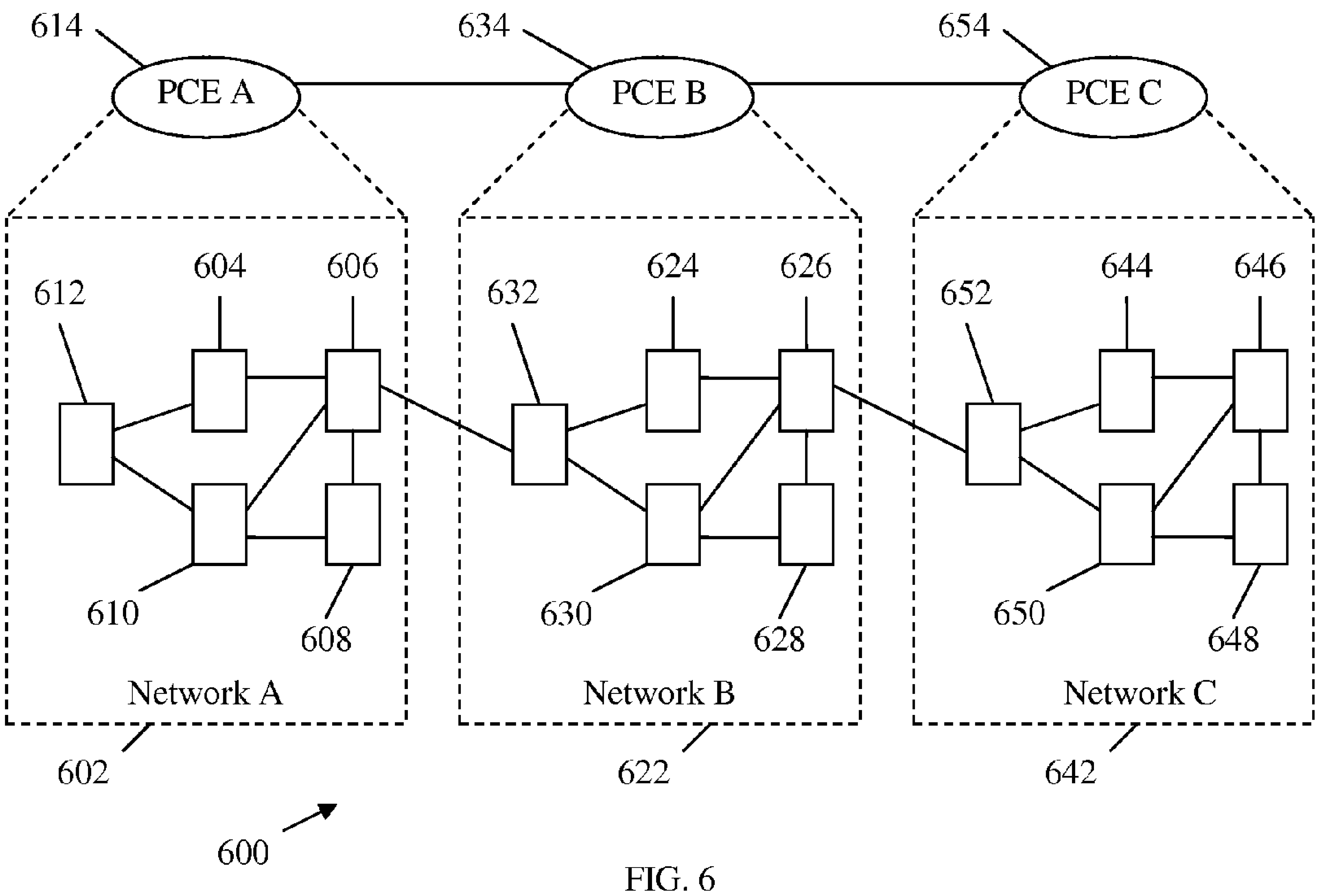
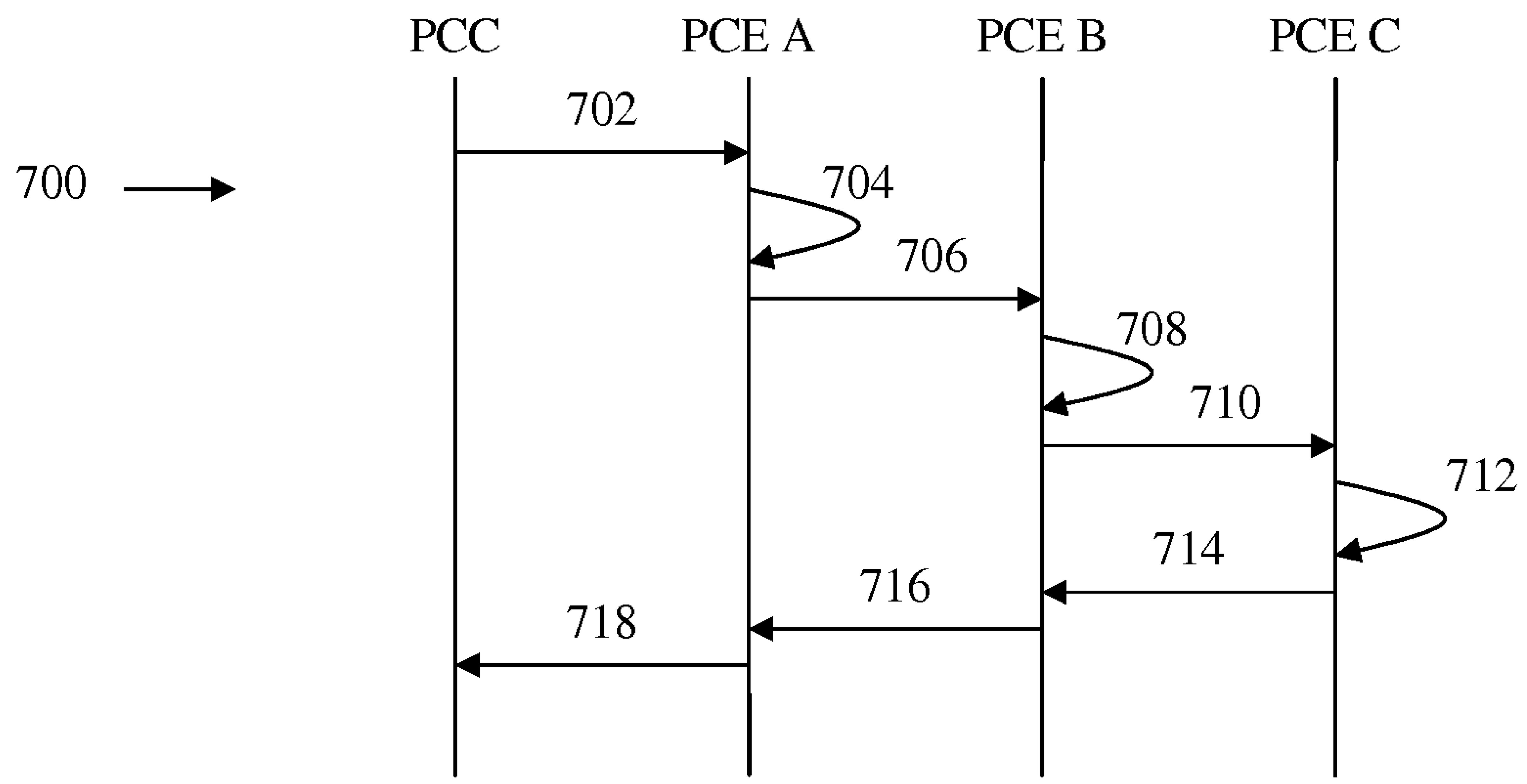

614
634
654
PCE A
PCE B
PCE C
612
604
606
632
624
626
652
644
646
610
608
630
628
650
648
Network A
Network B
Network C
602
622
642
600

FIG. 6


PCC
PCE A
PCE B
PCE C
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702
704
706
708
710
712
714
716
718

FIG. 7

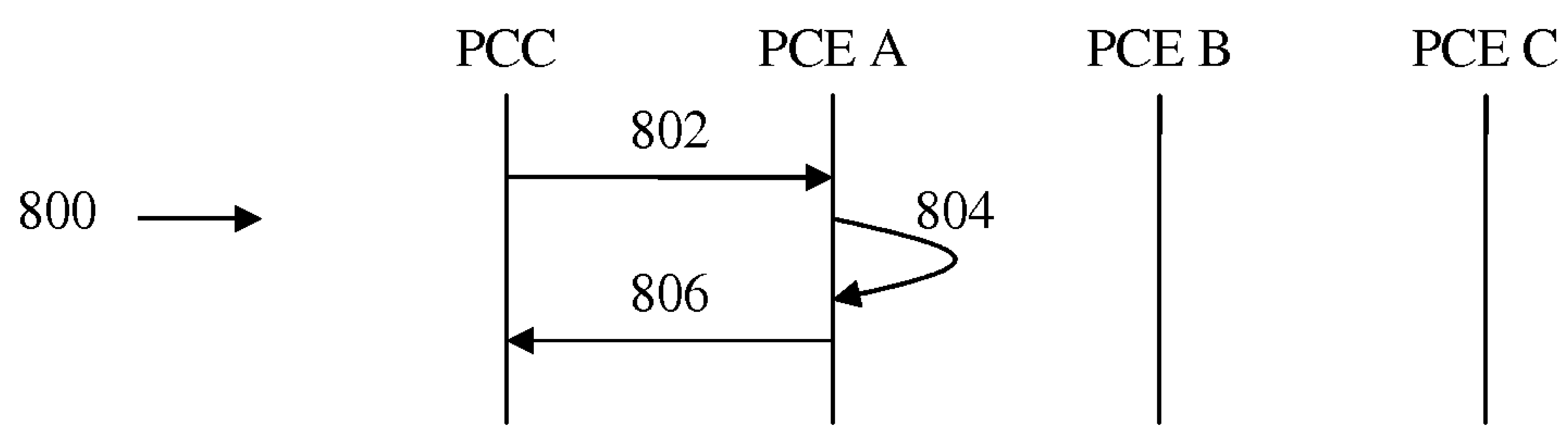
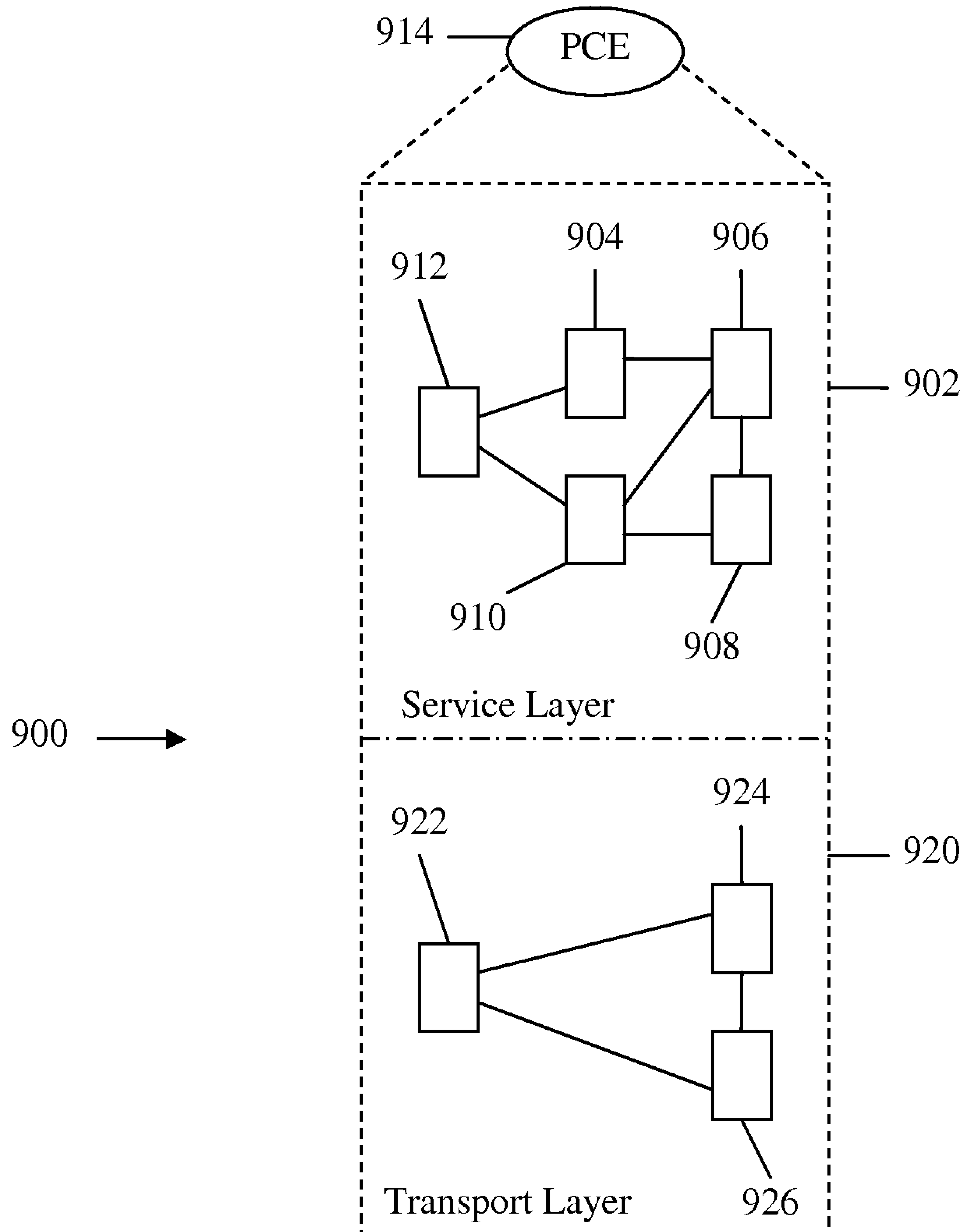

PCC
PCE A
PCE B
PCE C
800
802
804
806

FIG. 8


914
PCE
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904
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902
910
908
Service Layer
900
922
924
920
Transport Layer
926

FIG. 9

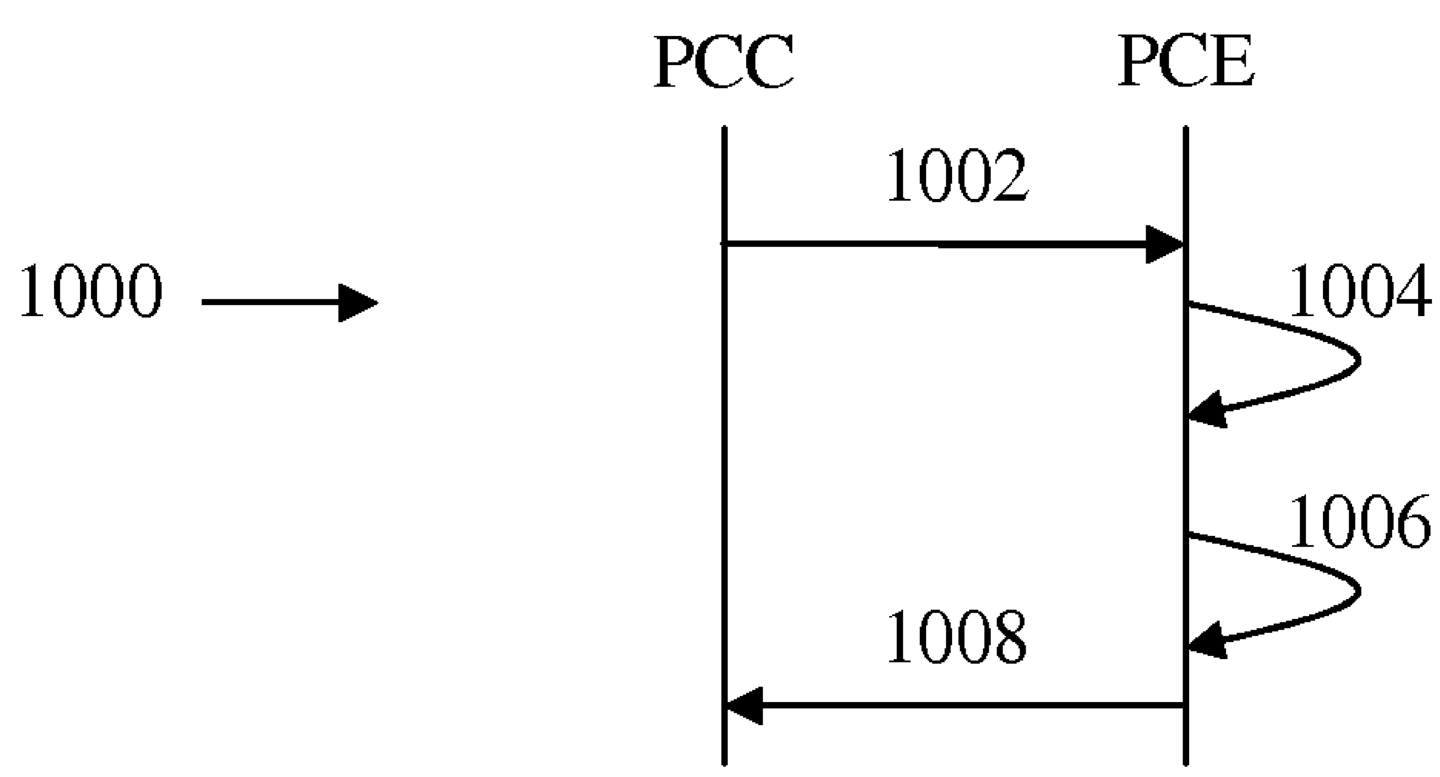

PCC
PCE
1002
1000
1004
1006
1008

FIG. 10

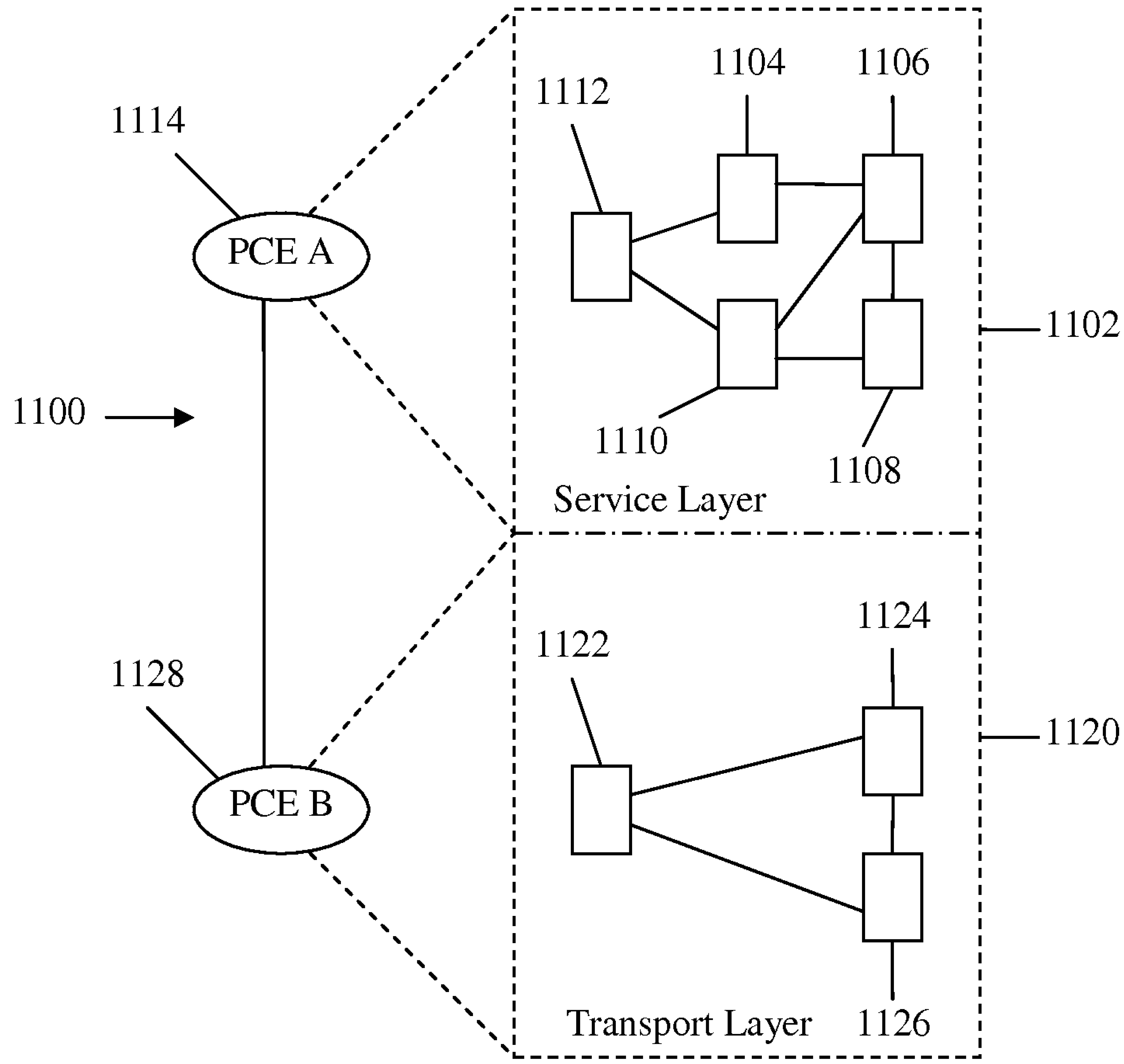
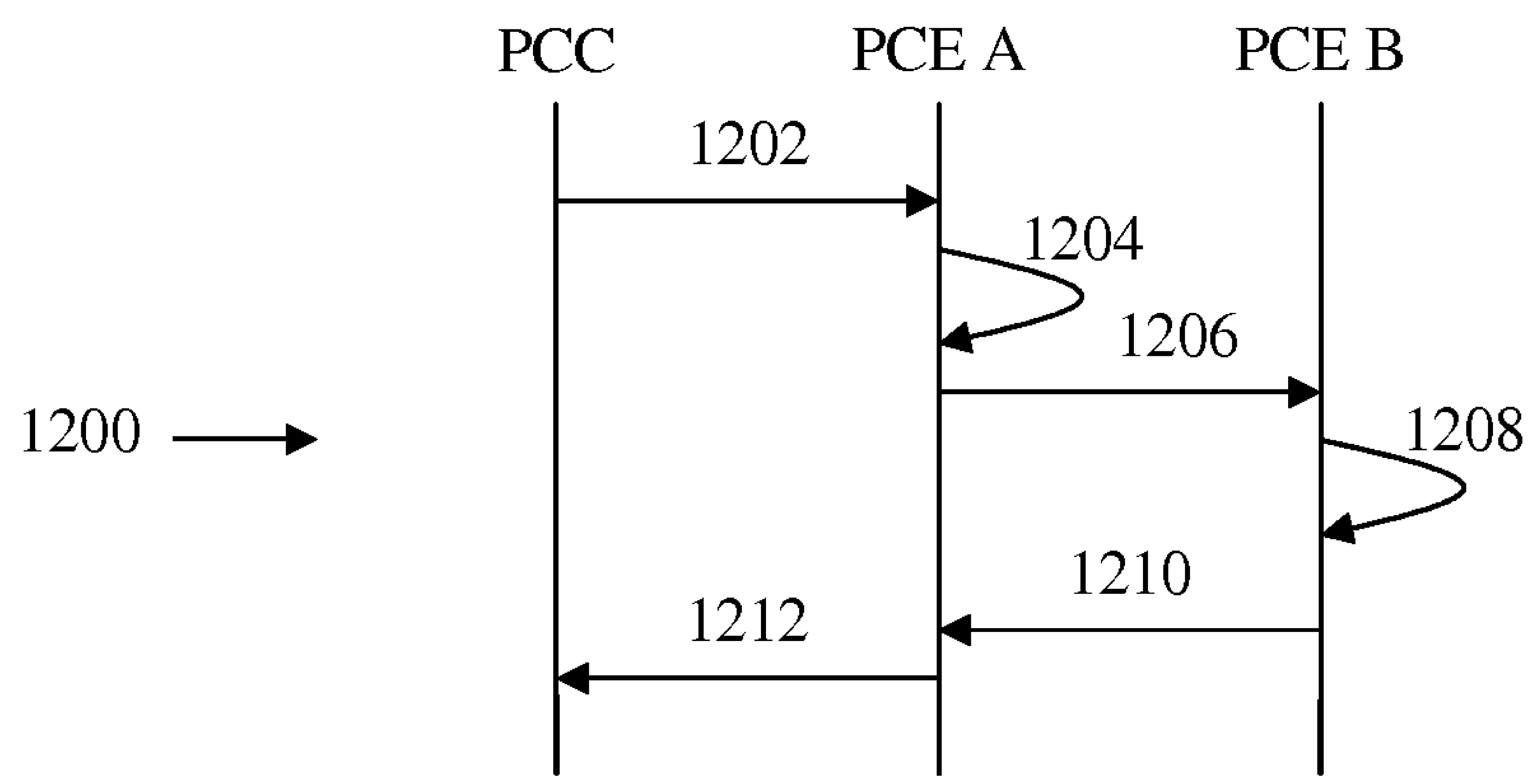

1114
1100
1128
PCE A
PCE B
1112
1104
1106
1102
1110
1108
Service Layer
1122
1124
1120
Transport Layer
1126

FIG. 11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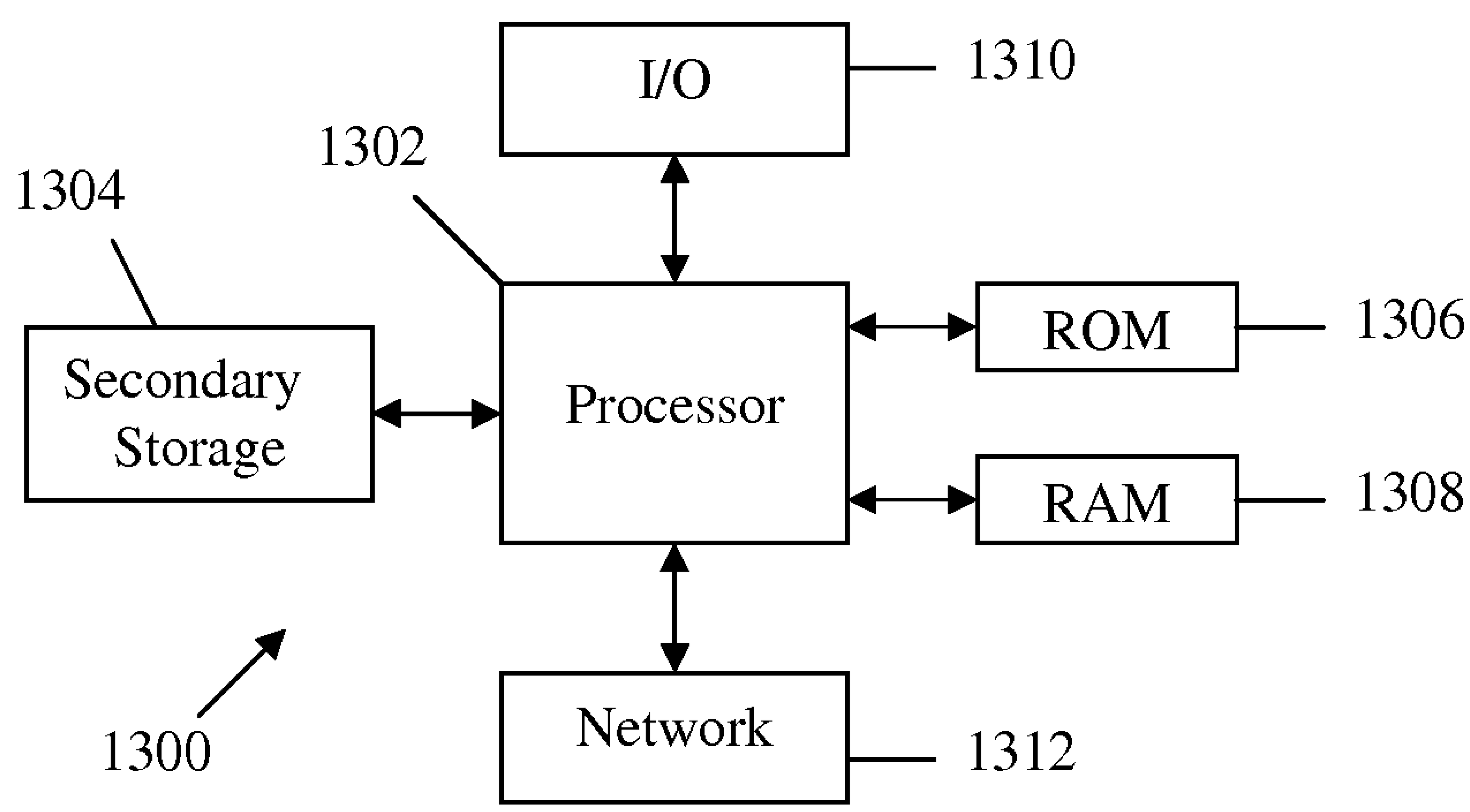
PCE A
PCE B
1202
1204
1206
1200
1208
1210
1212

FIG. 12


I/O
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1302
1304
Secondary Storage
Processor
ROM
1306
RAM
1308
1300
Network
1312

FIG. 13

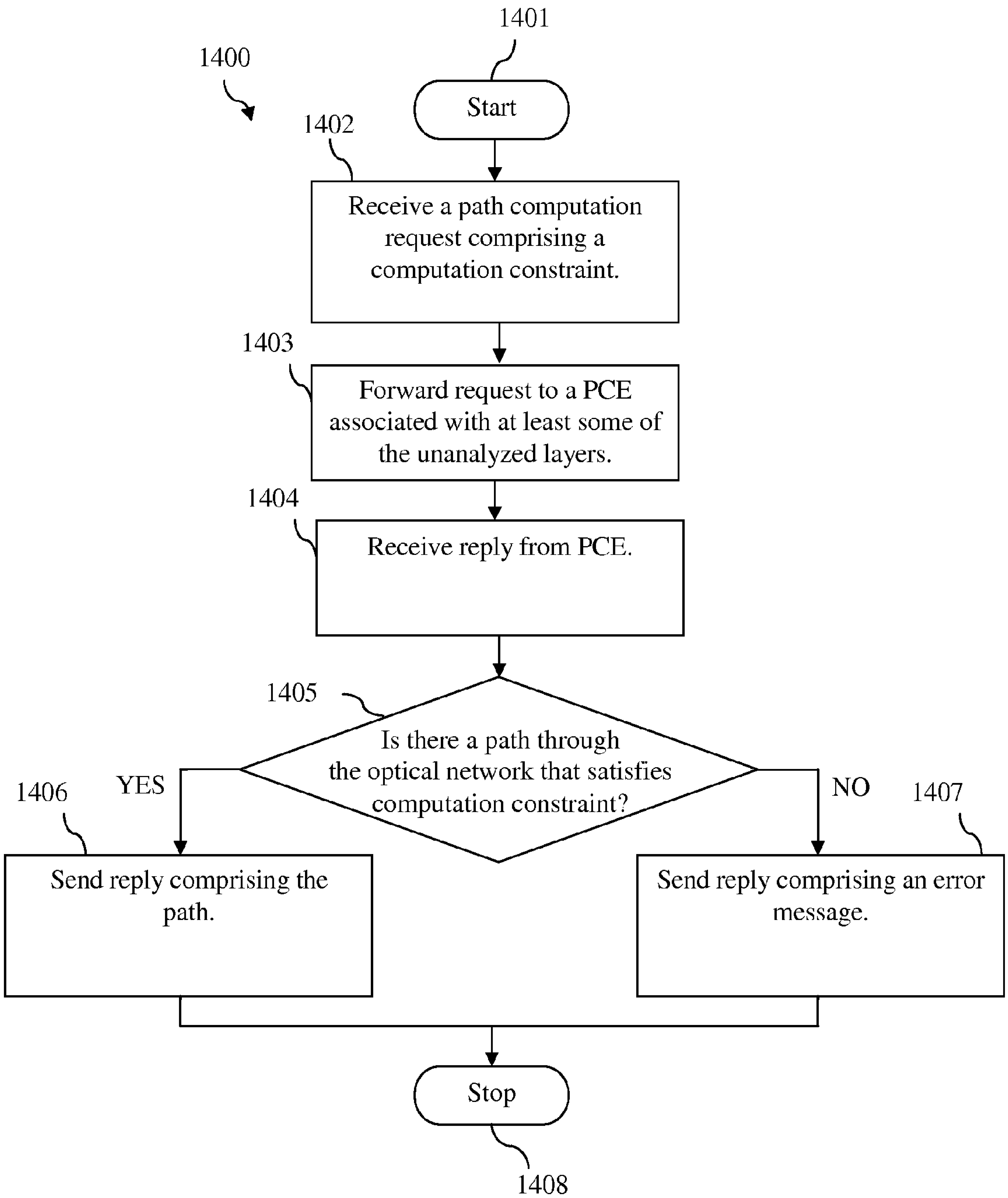
1400
1401
Start
1402
Receive a path computation request comprising a computation constraint.
1403
Forward request to a PCE associated with at least some of the unanalyzed layers.
1404
Receive reply from PCE.
1405
Is there a path through the optical network that satisfies computation constraint?
YES
NO
1406
Send reply comprising the path.
1407
Send reply comprising an error message.
Stop
1408

FIG. 14

# OPTICAL IMPAIRMENT AWARE PATH COMPUTATION ARCHITECTURE IN PCE BASED NETWORK

## CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a continuation of U.S. patent application Ser. No. 12/046,557, filed by Lee, et al. and entitled "Optical Impairment Aware Path Computation Architecture in PCE Based Network," which claims priority to U.S. Provisional Patent Application No. 60/895,283 filed Mar. 16, 2007 by Dunbar et al. and entitled "System for Optical Impairment Aware Path Computation Architecture in PCE Based Network", both of which are incorporated herein by reference as if reproduced their entireties.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

## REFERENCE TO A MICROFICHE APPENDIX

Not applicable.

## BACKGROUND

Wavelength division multiplexing (WDM) is one technology that is envisioned to increase bandwidth capability and enable bidirectional communications in optical networks. In WDM networks, multiple data signals can be transmitted simultaneously between network elements (NEs) using a single fiber. Specifically, the individual signals may be assigned different transmission wavelengths so that they do not interfere or collide with each other. The path that the signal takes through the network is referred to as the lightpath. One type of WDM network, a wavelength switched optical network (WSON), seeks to switch the optical signals with fewer optical-electrical-optical (OEO) conversions along the lightpath, e.g. at the individual NEs, than existing optical networks.

One of the challenges in implementing WDM networks is the determination of the path for the various signals that are being transported through the network at any given time. Unlike traditional circuit-switched and connection-oriented packet-switched networks that merely have to determine a route for the data stream across the network, WDM networks are burdened with the additional constraint of having to ensure that the same wavelength is not simultaneously used by two signals over a single fiber. This constraint is compounded by the fact that WDM networks typically use specific optical bands comprising a finite number of usable optical wavelengths. Path computations can also be constrained due to other issues, such as excessive optical noise, along the lightpath.

## SUMMARY

In one embodiment, the disclosure includes an apparatus comprising at least one processor configured to implement a method comprising receiving a path computation request comprising at least one path computation constraint, and determining whether there is a path through an optical network that satisfies the path computation constraints.

In another embodiment, the disclosure includes an apparatus configured to process a data structure comprising a flags



field comprising at least one flag having one of an active state or an inactive state, wherein each flag is representative of an optical quality constraint.

These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of this disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts.

FIG. **1** is a schematic diagram of an embodiment of a WSON system.

FIG. **2** is a protocol diagram of an embodiment of the communications between a path computation element (PCE) and a path computation client (PCC).

FIG. **3** is a schematic diagram of an embodiment of an optical quality constraint (OQC) object.

FIG. **4** is a schematic diagram of an embodiment of a type, length, and value (TLV) sub-object.

FIG. **5** is a schematic diagram of another embodiment of a TLV sub-object.

FIG. **6** is a schematic diagram of an embodiment of a multi-domain network architecture.

FIG. **7** is a protocol diagram of an embodiment of the communications in a multi-domain network architecture.

FIG. **8** is a protocol diagram of another embodiment of the communications in a multi-domain network architecture.

FIG. **9** is a schematic diagram of an embodiment of a multi-layer network architecture.

FIG. **10** is a protocol diagram of an embodiment of the communications in a multi-layer network architecture.

FIG. **11** is a schematic diagram of another embodiment of a multi-layer network architecture.

FIG. **12** is a protocol diagram of another embodiment of the communications in a multi-layer network architecture.

FIG. **13** is a schematic diagram of one embodiment of a general-purpose computer system.

FIG. **14** is a flowchart of an embodiment of a method.

## DETAILED DESCRIPTION

It should be understood at the outset that although an illustrative implementation of one or more embodiments are provided below, the disclosed systems and/or methods may be implemented using any number of techniques, whether currently known or in existence. The disclosure should in no way be limited to the illustrative implementations, drawings, and techniques illustrated below, including the exemplary designs and implementations illustrated and described herein, but may be modified within the scope of the appended claims along with their full scope of equivalents.

Disclosed herein is a method and system for including one or more path computation constraints in the PCE protocol (PCEP). Specifically, various types of path computation constraints are disclosed, as well as a communication protocol by which the PCE can consider the path computation constraints when performing its path computation for the PCC. Various alternatives are proposed whereby a plurality of PCEs each having authority over a different network communicate with each other and provide a unified path computation to the PCC. Alternatively, one or more PCEs may analyze a network at different layers, such as the service layer and the transport layer, to ensure that the path computation complies with the path computation constraints at each layer.

FIG. **1** illustrates one embodiment of a WSON system **100**. The system **100** may comprise a WSON **110**, a control plane controller **120**, and a PCE **130**. The WSON **110**, control plane controller **120**, and PCE **130** may communicate with each other via optical, electrical, or wireless means. The WSON **110** may comprise a plurality of NEs **112** coupled to one another using optical fibers. In an embodiment, the optical fibers may also be considered NEs **112**. The optical signals may be transported through the WSON **110** over lightpaths that may pass through some of the NEs **112**. In addition, some of the NEs **112**, for example those at the ends of the WSON **110**, may be configured to convert between electrical signals from external sources and the optical signals used in the WSON **110**. Although four NEs **112** are shown in the WSON **110**, the WSON **110** may comprise any number of NEs **112**.

The WSON **110** may be any optical network that uses active or passive components to transport optical signals. The WSON **110** may implement WDM to transport the optical signals through the WSON **110**, and may comprise various types of optical components. For example, the WSON **110** may comprise optical cross connects (OXC), photonic cross connects (PXC), reconfigurable optical add/drop multiplexers (ROADM), wavelength selective switches (WSS), fixed optical add/drop multiplexers (FOADM), and so forth. The WSON **110** may be part of a long haul network, a metropolitan network, or an access network.

The control plane controller **120** may coordinate activities within the WSON **110**. Specifically, the control plane controller **120** may receive optical connection requests and provide lightpath signaling to the WSON **110** via Multiprotocol Label Switching Traffic Engineering (MPLS-TE) or Generalized Multi-Protocol Label Switching (GMPLS), thereby coordinating the NEs **112** such that data signals are routed through the WSON **110** with little or no contention. In addition, the control plane controller **120** may communicate with the PCE **130** using PCEP to provide the PCE **130** with information that may be used for the path computation, and/or receive the path computation from the PCE **130** and forward the path computation to the NEs **112**. The control plane controller **120** may be located in a component outside of the WSON **110**, such as an external server, or may be located in a component within the WSON **110**, such as a NE **112**.

The PCE **130** may perform all or part of the path computation for the WSON system **100**. Specifically, the PCE **130** may determine the routes of Label Switched Paths (LSPs) through the network. As such, the PCE **130** may receive the path computation constraints that may be used for the path computation from the control plane controller **120**, from the NEs **112**, or both. The PCE **130** may use the path computation constraints when computing the routes, e.g. lightpaths, for the optical signals. The path computation may include at least one route for each incoming signal and optionally at least one wavelength associated with each route. The PCE **130** may then send the path computation to the control plane controller **120** or directly to the NEs **112**. To assist the PCE **130** in this process, the PCE **130** may comprise a global traffic-engineering database (TED), a path computation information database, an optical performance monitor (OPM), a physical layer constraint (PLC) information database, or combinations thereof. The PCE **130** may be located in a component outside of the WSON **110**, such as an external server, or may be located in a component within the WSON **110**, such as a NE **112**.

The NEs **112** may be coupled to each other via optical fibers. The optical fibers may be used to establish optical links and transport the optical signals between the NEs **112**. The optical fibers may comprise standard single mode fibers (SMFs) as defined in ITU-T standard G.652, dispersion shifted SMFs as defined in ITU-T standard G.653, cut-off shifted SMFs as defined in ITU-T standard G.654, non-zero dispersion shifted SMFs as defined in ITU-T standard G.655, wideband non-zero dispersion shifted SMFs as defined in ITU-T standard G.656, or combinations thereof. These fiber types may be differentiated by their optical impairment characteristics, such as attenuation, chromatic dispersion, polarization mode dispersion (PMD), four wave mixing, or combinations thereof. These effects may be dependent upon wavelength, channel spacing, input power level, or combinations thereof. The optical fibers may be used to transport WDM signals, such as course WDM (CWDM) signals as defined in ITU-T G.694.2 or dense WDM (DWDM) signals as defined in ITU-T G.694.1. All of the standards described herein are incorporated herein by reference.

In some embodiments, the PCE **130** may receive a path computation request from a PCC. The PCC may be any client application requesting a path computation to be performed by the PCE **130**. The PCC may also be any network component that makes such a request, such as the control plane controller **120**, or any NE **112**, such as a ROADM or a FOADM. Generally, the PCC communicates with the PCE **130** using PCEP, although other acceptable communications protocol may be used as well.

There may be many types of path computation constraints that can affect the path computation. In one embodiment, the path computation constraints include optical quality constraints. Examples of such include the optical signal-to-noise ratio (OSNR), amplifier spontaneous emission (ASE), PMD, polarization-dependent loss (PDL), coherent optical crosstalk, incoherent optical crosstalk, effective pass-band, gain non-uniformity, gain transients, and chromatic dispersion. In some embodiments, the path computation constraints may be classified as linear in that their effects are independent of the optical signal power and they affect the wavelengths individually. Alternatively, the path computation constraints may be classified as nonlinear in that their effects are dependent of the optical signal power, generate dispersion on a plurality of wavelength channels, and induce crosstalk between wavelength channels. Regardless, the path computation constraints are communicated to the PCE **130** so that the PCE **130** may consider them when computing a signal's path through the WSON **100**.

FIG. **2** illustrates an embodiment of a path computation communication method **200** between the PCC and the PCE. The method **200** may be implemented using any suitable protocol, such as the PCEP. The method **200** begins when the PCC sends a path computation request **202** to the PCE. The request **202** may comprises the OQC object described below. In some embodiments, the request **202** may comprise an indication of the need for a given source-destination (S-D) path through the network. At **204**, the PCE calculates a path through the network that meets the path computation constraints and any other network constraints. The PCE then sends a path computation reply **206** to the PCC. The reply **206** may comprise one or more paths through the network, which may be embodied as the OQC object and TLVs described below. In some embodiments, the reply **206** may comprise an indication whether the requested S-D path satisfies the path computation constraints. If the PCE is not able to calculate a path through the network that satisfies the path computation constraints, then the reply **206** may contain an error message that indicates that the PCE is not able to calculate a path through the network that satisfies the path computation constraints. Alternatively, if the PCE is not allowed to calculate a path through the network, then the reply **206** may contain an error message that indicates that the PCE is not allowed to calculate a path through the network, for example, due to policy reasons.

FIG. **3** illustrates an embodiment of the OQC object **300** that may be included in the request and reply messages described herein. The OQC object **300** may comprise a reserved field **302**, a flags field **304** comprising one or more flags, such as an N flag **306** and a P flag **308**, and optionally one or more TLVs **310**. The reserved field **302** may comprise the first about 10 bits of the OQC object **300** and may be reserved for uses by the PCC and PCE unrelated to the path computation constraints. The flags field **304** may comprise the subsequent about 22 bits of the OQC object **300** and may comprise one or more flags. Each flag may be related to one or more path computation constraints, such as the optical quality constraints. The flags may be any length and may be positioned anywhere and in any order in the flags field **304**, but in an embodiment, each flag is about one bit in length and the flags are justified to the right of the flags field **304** in a predetermined order. In such a case, the presence of a one bit in a particular location may indicate that a particular path computation constraint exists or is applicable to the path computation request or reply. Alternatively, a zero bit in a particular location may indicate that the particular path computation constraint does not exist or is not applicable to the path computation request or reply. The presence of the one bit or the zero bit in the flags field **304** may also have differing meaning depending on whether the one bit or the zero bit is part of the request or the reply. The TLVs **310** may be associated with the flags in the flags field **304**, and may provide more information regarding the path computation constraints.

For example and as shown in FIG. **3**, the $31^{st}$ bit in the OQC object **300** may be the N flag **306**. The N flag **306** may be associated with the OSNR associated with the path. When the N flag **306** is set to zero in the request, it may indicate that the OSNR does not have to be considered in the path computation. When the N flag **306** is set to one in the request, it may indicate that the OSNR should be considered in the path computation. In such a case, the OQC object **300** may comprise a TLV **310** that contains further details regarding the OSNR, such as a value for the upper limit of the OSNR. When the N flag **306** is set to zero in the reply, it may indicate that the computed path does not comply with the OSNR constraint, further details of which may be included in a TLV **310**. When the N flag **306** is set to one in the reply, it may indicate that the computed path complies with the OSNR constraint.

Similarly, the $32^{nd}$ bit in the OQC object **300** may be the P flag **308**. The P flag **308** may be associated with the PMD associated with the path. When the P flag **308** is set to zero in the request, it may indicate that the PMD does not have to be considered in the path computation. When the P flag **308** is set to one in the request, it may indicate that the PMD should be considered in the path computation. In such a case, the OQC object **300** may comprise a TLV **310** that contains further details regarding the PMD, such as a value for the upper limit of the PMD. When the P flag **308** is set to zero in the reply, it may indicate that the computed path does not comply with the PMD constraint, further details of which may be included in a TLV **310**. When the P flag **308** is set to one in the reply, it may indicate that the computed path complies with the PMD constraint.

FIG. **4** illustrates one embodiment of a TLV **400** that may be associated with the N flag in the OQC object. The TLV **400** may comprise a type field **402**, a length field **404**, and a value field **406**. The type field **402** may comprise the first about 16 bits of the TLV **400** and may associate the TLV **400** with the N flag in the OQC object. The length field **404** may be the subsequent about 16 bits and may indicate the size of the value field **406** in bytes. The value field **406** may be any size, but in some embodiments is the subsequent about 32 bits on the TLV **400**. The value field **406** may contain information related to the OSNR, such as the OSNR upper limit for the path or other OSNR impairment factor details.

FIG. **5** illustrates one embodiment of a TLV **500** that may be associated with the P flag in the OQC object. The TLV **500** may comprise a type field **502**, a length field **504**, and a value field **506**. The type field **502** may comprise the first about 16 bits of the TLV **500** and may associate the TLV **500** with the P flag in the OQC object. The length field **504** may be the subsequent about 16 bits and may indicate the size of the value field **506** in bytes. The value field **506** may be any size, but in some embodiments is the subsequent about 32 bits on the TLV **500**. The value field **506** may contain information related to the PMD, such as the PMD upper limit for the path or other PMD impairment factor details.

FIG. **6** illustrates an embodiment of a multi-domain network architecture **600** that may be used to illustrate the concepts described herein. The multi-domain network architecture **600** may comprise three networks: network A **602**, network B **622**, and network C **642**, which may each be similar to the WSON described above. Network A **602** may comprise PCE A **614** and nodes **604**, **606**, **608**, **610**, and **612** (collectively **604-612**). Similarly, Network B **622** may comprise PCE B **634** and nodes **624**, **626**, **628**, **630**, and **632** (collectively **624-632**), and Network C **642** may comprise PCE C **654** and nodes **644**, **646**, **648**, **650**, and **652** (collectively **644-652**). PCE A **614** can communicate with each of the nodes **604-612** and can calculate paths subject to path computation constraints within network A **602**. Similarly, PCE B **634** can communicate with each of the nodes **624-632** and can calculate paths subject to path computation constraints within network B **622**, and PCE C **654** can communicate with each of the nodes **644-652** and can calculate paths subject to path computation constraints within network C **642**. In addition, the various components within the multi-domain network architecture **600** are coupled to and can communicate with each other as indicated by the solid lines in FIG. **6**. It will be appreciated that while FIG. **6** is described in the context of a multi-domain network architecture, the concepts described herein are also applicable to situations where multiple PCEs are responsible for certain sections of a single network.

FIG. **7** illustrates one embodiment of a path computation communication method **700** between the PCC and the PCEs for the three networks illustrated in FIG. **6**. Specifically, FIG. **7** illustrates the case where the path computation is performed by multiple PCEs, and each PCE may indicate whether the path computation constraints have been satisfied within the network or network portion of the path for which the PCE is responsible. The method **700** may be implemented using any suitable protocol, such as the PCEP. The method **700** begins when the PCC sends a path computation request **702** to one of the PCEs, such as PCE A. The request **702** may comprises the OQC object described above. In some embodiments, the request **702** may comprise an indication of the need for a path computation for a given S-D path in one or more of networks A, B, and C. At **704**, PCE A calculates a path through network A that meets the path computation constraints and any other network constraints. For example, PCE A may determine that a path through nodes **612**, **604**, and **606** meets the path computation constraints for network A. Assuming that PCE A can calculate a path that meets the path computation constraints for network A, PCE A forwards the request **706** to PCE B. At **708**, PCE B calculates a path through network B that meets the path computation constraints and any other network constraints. For example, PCE B may determine that a path through nodes **632**, **630**, and **626** meets the path computation constraints for network B. Assuming that PCE B can calculate a path that meets the path computation constraints for network B, PCE B forwards the request **710** to PCE C.

At **712**, PCE C calculates a path through network C that meets the path computation constraints and any other network constraints. In some cases, PCE C may be able to calculate a path that meets the path computation constraints for network C. For example, PCE C may determine that a path through nodes **652**, **650**, **648**, and **646** meets the path computation constraints for network C. In such cases, PCE C may add the path and any information related to the path to a reply **714**, and sends the reply **714** to PCE B. In other cases, PCE C may not be able to calculate a path that meets the path computation constraints for network C. For example, PCE C may determine that no path through network C meets the path computation constraints for network C. In such cases, PCE C may add one of the error messages described above and an optional explanation to the reply **714**, and may send the reply **714** to PCE B. In either case, the reply **714** may comprise the OQC object described above, which may include at least one path, at least one error message, and/or at least one indication whether the requested S-D path satisfies the path computation constraints. Upon receiving the reply **714**, PCE B may include the path through network B and any other related information in the reply **716** sent to PCE A. Upon receiving the reply **716**, PCE A may include the path through network A and any other related information in the reply **718** sent to the PCC. Thus, upon receipt of the reply **718**, the PCC knows whether a path through the networks A, B, and C exists, and if not, the location of and reason for the path computation failure. It will also be appreciated that in some embodiments the various PCEs may add one or more of their paths to the request as it is propagated through the networks, rather than adding their paths to the reply as it is returned through the networks.

FIG. **8** illustrates another embodiment of a path computation communication method **800** between the PCC and the PCEs for the three networks illustrated in FIG. **6**. Specifically, FIG. **8** illustrates the case where the path computation is performed by multiple PCEs, but the path computation fails at the first PCE, e.g. PCE A. The method **800** may be implemented using any suitable protocol, such as the PCEP. The method **800** begins when the PCC sends a path computation request **802** to one of the PCEs, such as PCE A. The request **802** may comprises the OQC object described above. In some embodiments, the request **802** may comprise an indication of the need for a path computation for a given S-D path in one or more of networks A, B, and C. At **804**, PCE A attempts to calculate a path through network A that meets the path computation constraints and any other network constraints. In this case, PCE A may not be able to calculate a path that meets the path computation constraints for network A. For example, PCE A may determine that no path through network A meets the path computation constraints for network A. Thus, PCE A may add one of the error messages described above and an optional explanation to the reply **806**, and sends the reply **806** to the PCC. Thus, the method **800** does not forward requests through the various networks when no path meeting the path computation constraints can be found in the first network. It will also be appreciated that the communications between the PCC and the PCEs may be any combination of methods **700** and **800** and/or modified by some policy, for example where the request is forwarded to the next PCE unless more than one of the path computation constraints cannot be met.

FIG. **9** illustrates an embodiment of a multi-layer network architecture **900** that may be used to illustrate the concepts described herein. The multi-layer network architecture **900** may be similar to the WSON described above and may comprise a PCE **914** and two layers: a service layer **902** and a transport layer **920**. The service layer **902** may comprise nodes **904**, **906**, **908**, **910**, and **912** (collectively **904-912**), and the transport layer **920** may comprise nodes **922**, **924**, and **926** (collectively **922-926**). In some embodiments, at least some of the nodes **904-912** may be the same physical structure as at least some of the nodes **922-926**, but wherein the nodes **904-912** are separated from the nodes **922-926** by one or more logical partitions. The PCE **914** can communicate with each of the nodes **904-912** and **922-926** and can calculate paths subject to path computation constraints within the service layer **902** and the transport layer **920**. In addition, the various components within the multi-layer network architecture **900** have the topologies as shown in that they are coupled to and can communicate with each other as indicated by the solid lines in FIG. **9**. It will be appreciated that while FIG. **9** is described in the context of a single multi-layer network architecture, the concepts described herein are also applicable to situations where one or more PCEs are responsible for a plurality of path computations in a plurality of multi-layer networks.

FIG. **10** illustrates an embodiment of a path computation communication method **1000** between the PCC and the PCE for the network illustrated in FIG. **9**. Specifically, FIG. **10** illustrates the case where the path computation for multiple layers within a single network is performed by a single PCE. The method **1000** may be implemented using any suitable protocol, such as the PCEP. The method **1000** begins when the PCC sends a path computation request **1002** to the PCE. The request **1002** may comprises the OQC object described above. In some embodiments, the request **1002** may comprise an indication of the need for a path computation for a given S-D path in the service layer, the transport layer, or both. At **1004**, the PCE calculates a path through the service layer that meets the path computation constraints and any other network constraints. For example, the PCE may determine that a path through nodes **912**, **904**, and **906** meets the path computation constraints for the service layer. Assuming that the PCE can calculate a path that meets the path computation constraints for the service layer, the PCE verifies whether the path selected at **1004** meets the path computation constraints and any other network constraints of the transport layer at **1006**. In some cases, the path selected at **1004** meets the path computation constraints and any other network constraints for the transport layer. For example, the PCE may determine that a path through nodes **922** and **924** meets the path computation constraints for the transport layer. In such cases, the PCE adds the path and any information related to the path to a reply **1008**, and sends the reply **1008** to the PCC.

In other cases, the path selected at **1004** may not meet one or more of the path computation constraints and any other network constraints for the transport layer. For example, the PCE may determine that a path through nodes **922** and **924** does not meet the path computation constraints for transport layer. In such cases, the PCE will analyze alternative and perhaps less optimal paths through the service layer and the transport layer to determine if there are any paths that satisfy the path computation constraints for both the service layer and the transport layer. For example, the path through nodes **912**, **910**, and **908** may satisfy the service layer path computation constraints while also satisfying the transport layer path computation constraints for the transport layer nodes **922**, **926**, and **924**. If such a path is found, the PCE may include the path and any other related information in the reply **1008** sent to the PCC. If such a path is not found, the PCE may include one of the error messages described above and an optional explanation in the reply **1008** sent to the PCC. In any event, the reply **1008** may comprise the OQC object described above, which may comprise at least one path, at least one error message, and/or at least one indication whether the requested S-D path satisfies the path computation constraints. Thus, upon receipt of the reply **1008**, the PCC knows whether a path through the service layer and transport layer exists, and if not, the location of and reason for the path computation failure.

FIG. **11** illustrates an embodiment of a multi-layer network architecture **1100** that may be used to illustrate the concepts described herein. The multi-layer network architecture **1100** may be similar to the WSON described above, and may comprises two PCEs, PCE A **1114** and PCE B **1128**, and two layers, a service layer **1102** and a transport layer **1120**. The service layer **1102** may comprise nodes **1104**, **1106**, **1108**, **1110**, and **1112** (collectively **1104-1112**), and transport layer **1120** may comprise nodes **1122**, **1124**, and **1126** (collectively **1122-1126**). In some embodiments, at least some of the nodes **1104-1112** may be the same physical structure as at least some of the nodes **1122-1126**, but wherein the nodes **1104-1112** are separated from the nodes **1122-1126** by one or more logical partitions. PCE A **1114** can communicate with each of the nodes **1104-1112** and can calculate paths subject to path computation constraints within the service layer **1102**, while PCE B **1128** can communicate with each of the nodes **1122-1126** and can calculate paths subject to path computation constraints within transport layer **1120**. In addition, the various components within the multi-layer network architecture **1100** have the topologies as shown in that they are coupled to and can communicate with each other as indicated by the solid lines in FIG. **11**. It will be appreciated that while FIG. **11** is described in the context of a single multi-layer network architecture, the concepts described herein are also applicable to situations where a single PCE is responsible for one or more layers in multiple networks.

FIG. **12** illustrates another embodiment of a path computation communication method **1200** between the PCC and the two PCEs for the network illustrated in FIG. **11**. Specifically, FIG. **12** illustrates the case where the path computation for each layer is performed by a separate PCE. The method **1200** may be implemented using any suitable protocol, such as the PCEP. The method **1200** begins when the PCC sends a path computation request **1202** to PCE A. The request **1202** may comprise the OQC object described above. In some embodiments, the request **1202** may comprise an indication of the need for a path computation for a given S-D path in the service layer, the transport layer, or both. At **1204**, PCE A calculates a path through the service layer that meets the path computation constraints and any other network constraints. For example, PCE A may determine that a path through nodes **1112**, **1104**, and **1106** meets the path computation constraints for the service layer. If there is not a path through the service layer that meets the path computation constraints and any other network constraints, then the PCE A can send a reply message to the PCC with one of the error messages described above. Assuming that PCE A can calculate a path that meets the path computation constraints and any other network constraints, PCE A includes the path in the request **1206** sent to PCE B. Upon receipt of the request **1206**, PCE B verifies whether the path selected at **1204** meets the path computation constraints and any other network constraints for the transport layer at **1208**. In some cases, the path selected at **1204** meets the path computation constraints and any other network constraints for the transport layer. For example, PCE B may determine that a path through nodes **1122** and **1124** meets the path computation constraints for transport layer. In such cases, PCE B includes the path and any other related information in the reply **1210** sent to PCE A. PCE A then forwards the reply **1212** back to the PCC.

In other cases, the path selected at **1204** may not meet one or more of the path computation constraints and any other network constraints for the transport layer. For example, PCE B may determine that the path through nodes **1122** and **1124** does not meet the path computation constraints for transport layer. In such cases, PCE B will analyze alternative and perhaps less optimal paths through the transport layer to determine if there are any paths that satisfy the path computation constraints for the transport layer. For example, the path through nodes **1122**, **1126**, and **1124** may satisfy the transport layer path computation constraints. If such a path is not found, PCE B may include one of the error messages described above and an optional explanation in the reply **1210** sent to PCE A. If such a path is found, PCE B may include the path and any related information in the reply **1210** sent to PCE A. Upon receipt of a reply **1210** with an alternate path, PCE A verifies whether the alternate path selected at **1208** meets the path computation constraints and any other network constraints for the service layer. If the alternate path selected at **1208** meets the path computation constraints and any other network constraints for the service layer, PCE A may adopt the alternate path as the service layer path, and may include the alternate path in the reply **1212** sent to the PCC. If the path selected at **1208** does not meet the path computation constraints and any other network constraints of the service layer, then PCEs A and B can repeat the steps **1204**, **1206**, **1208**, and **1210** until either a path satisfying the path computation constraints for both the service layer and the transport layer is found, or it is determined that there is not a path that satisfies the path computation constraints for both the service layer and the transport layer. After such, the path or an error message is included in the reply **1212** sent to the PCC. In some embodiments, PCE A may add a plurality of paths to the request **1206** so that PCE B can verify each of the paths and indicate such in the reply **1210**. If there are multiple valid paths, PCE A can choose to keep one or more of these paths in the reply **1210**, and forward the reply **1212** to the PCC. In any event, the reply **1212** may comprise the OQC object described above, which may comprise at least one path, at least one error message, and/or at least one indication whether the requested S-D path satisfies the path computation constraints. Thus, upon receipt of the reply **1212**, the PCC knows whether a path through the service layer and transport layer exists, and if not, the location of and reason for the path computation failure.

The network components described above may be implemented on any general-purpose network component, such as a computer or network component with sufficient processing power, memory resources, and network throughput capability to handle the necessary workload placed upon it. FIG. **13** illustrates a typical, general-purpose network component suitable for implementing one or more embodiments of the components disclosed herein. The network component **1300** includes a processor **1302** (which may be referred to as a central processor unit or CPU) that is in communication with memory devices including secondary storage **1304**, read only memory (ROM) **1306**, random access memory (RAM) **1308**, input/output (I/O) devices **1310**, and network connectivity devices **1312**. The processor may be implemented as one or more CPU chips, or may be part of one or more application specific integrated circuits (ASICs).

The secondary storage **1304** is typically comprised of one or more disk drives or tape drives and is used for non-volatile storage of data and as an over-flow data storage device if RAM **1308** is not large enough to hold all working data. Secondary storage **1304** may be used to store programs that are loaded into RAM **1308** when such programs are selected for execution. The ROM **1306** is used to store instructions and perhaps data that are read during program execution. ROM **1306** is a non-volatile memory device that typically has a small memory capacity relative to the larger memory capacity of secondary storage **1304**. The RAM **1308** is used to store volatile data and perhaps to store instructions. Access to both ROM **1306** and RAM **1308** is typically faster than to secondary storage **1304**.

FIG. **14** is a flowchart that illustrates an embodiment of method **1400** which may be implemented by the processor of a PCC. The method **1400** starts at **1401** when a path computation request comprising a computation constraint is received at **1402**. Upon receiving the request, the request is forwarded to a PCE associated with at least some of the unanalyzed network layers at **1403**. Once a reply is received from the PCE at **1404**, a determination is made as to whether there is a path through the optical network that satisfies the path computation constraints at **1405**. If there is at least one path through the optical network that satisfies the path computation constraints, a reply that comprises the path is sent to the source of the initial request at **1406**. If there is not a path through the optical network that satisfies the path computation constraints, a reply that comprises an error message is sent to the source of the initial request at **1407**. The method stops at **1408**.

While several embodiments have been provided in the present disclosure, it should be understood that the disclosed systems and methods might be embodied in many other specific forms without departing from the spirit or scope of the present disclosure. The present examples are to be considered as illustrative and not restrictive, and the intention is not to be limited to the details given herein. For example, the various elements or components may be combined or integrated in another system or certain features may be omitted, or not implemented.

In addition, techniques, systems, subsystems, and methods described and illustrated in the various embodiments as discrete or separate may be combined or integrated with other systems, modules, techniques, or methods without departing from the scope of the present disclosure. Other items shown or discussed as coupled or directly coupled or communicating with each other may be indirectly coupled or communicating through some interface, device, or intermediate component whether electrically, mechanically, or otherwise. Other examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the spirit and scope disclosed herein.

What is claimed is:

**1**. A method implemented in a first Path Computation Element (PCE) operating in a first Wavelength Switched Optical Network (WSON) layer, wherein the method comprises:

receiving a path computation request from a second PCE operating in a second WSON layer associated with services, wherein the path computation request comprises:
- a logical service path across the second WSON layer; and
- a plurality of first flags that indicate whether one or more first WSON layer optical quality constraints are applicable to the path computation request;

verifying the logical service path of the second WSON layer according to the first WSON layer optical quality constraints by:
- computing a lightpath for the logical service path across the first WSON layer for transporting optical signals;
- receiving one or more optical impairment characteristics from nodes along the lightpath via signaling;
- performing an optical impairment computation of the lightpath by employing at least one of the optical impairment characteristics that corresponds to the first WSON layer optical quality constraints from the path computation request; and
- making a decision on an optical impairment validity of the lightpath based on the optical impairment computation resulting in an impairment validated lightpath; and

transmitting a path computation reply to the second PCE, wherein the path computation reply comprises:
- the impairment validated lightpath as part of an impairment validated routing and wavelength assignment (RWA) across a plurality of WSON layers in a single network domain; and
- a plurality of second flags that indicate impairment validity statuses of the impairment validated lightpath corresponding to the first WSON layer optical quality constraints from the path computation request.

**2**. The method of claim **1**, wherein the optical impairment characteristics are selected from a group of Optical Signal to Noise Ratio (OSNR) and dispersion.

**3**. The method of claim **1**, wherein the optical impairment characteristics are not distributed between the WSON layers.

**4**. The method of claim **1**, wherein the path computation request is received from the second PCE using PCE Protocol (PCEP).

**5**. The method of claim **1**, wherein the path computation reply is transmitted to the second PCE using PCE Protocol (PCEP).

**6**. The method of claim **1**, wherein the second WSON layer is a service layer, and wherein the first WSON layer is a transport layer.

**7**. An apparatus configured to implement a first Path Computation Element (PCE) operating in a first Wavelength Switched Optical Network (WSON) layer comprising:

at least one processor configured to:
- receive a first path computation request from a Path Computation Client (PCC);
- compute a logical service path across the first WSON layer according to the first path computation request;
- receive one or more impairment characteristics from a node along the logical service path via signaling;
- perform an impairment computation on the logical service path by employing at least one of the impairment characteristics;
- make a decision on an impairment validity of the logical service path based on at least one impairment characteristic;
- transmit a second path computation request to a second PCE operating in a second WSON layer that transports optical signals, wherein the second path computation request comprises:
  - a lightpath impairment validation request for the computed logical service path; and
  - a plurality of first flags that indicate whether one or more optical quality constraints are applicable to the second path computation request;

receive a first path computation reply from the second PCE, wherein the first path computation reply comprises:

an optical impairment validated lightpath associated with the logical service path; and

a plurality of second flags that indicate impairment validity statuses of the optical impairment validated lightpath across the second WSON layer corresponding to the optical quality constraints from the second path computation request; and

transmit a second path computation reply to the PCC comprising the optical impairment validated lightpath as part of an impairment validated routing and wavelength assignment (RWA) across a plurality of WSON layers in a single network domain.

**8**. The apparatus of claim **7**, wherein the optical quality constraints are selected from a group of Optical Signal to Noise Ratio (OSNR) and dispersion.

**9**. The apparatus of claim **7**, wherein the processor is further configured to receive a path computation constraint from the PCC, and wherein the impairment validity of the logical service path is further based on the path computation constraint.

**10**. The apparatus of claim **7**, wherein the impairment characteristics are not distributed between the WSON layers.

**11**. The apparatus of claim **7**, wherein the first path computation reply is received from the second PCE using PCE Protocol (PCEP).

**12**. The apparatus of claim **7**, wherein the second path computation request is transmitted to the second PCE using PCE Protocol (PCEP).

**13**. The apparatus of claim **7**, wherein the second path computation reply is transmitted to the PCC using PCE Protocol (PCEP).

**14**. The apparatus of claim **7**, wherein the first WSON layer is a service layer, and wherein the second WSON layer is a transport layer.

**15**. The apparatus of claim **7**, wherein the processor is further configured to receive the first flags from the PCC.

**16**. The apparatus of claim **7**, wherein the first path computation request is received from the PCC using PCE protocol (PCEP).

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